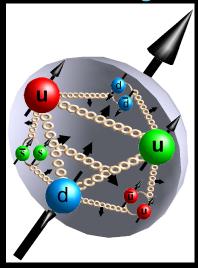
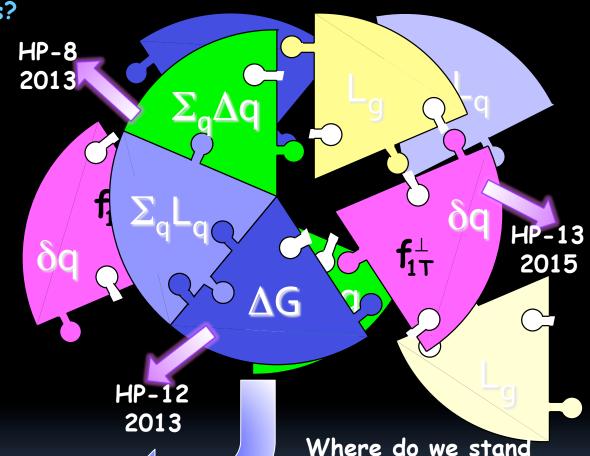
# THE RHIC SPIN PROGRAM THE QUEST FOR THE SPIN OF THE PROTON



### How do the partons form the spin of protons

Is the proton looking like this?





"Helicity sum rule"

$$\frac{1}{2}\hbar = \left\langle P, \frac{1}{2} | J_{QCD}^{z} | P, \frac{1}{2} \right\rangle = \sum_{q} \frac{1}{2} S_{q}^{z} + S_{g}^{z} + \sum_{q} L_{q}^{z} + L_{g}^{z}$$

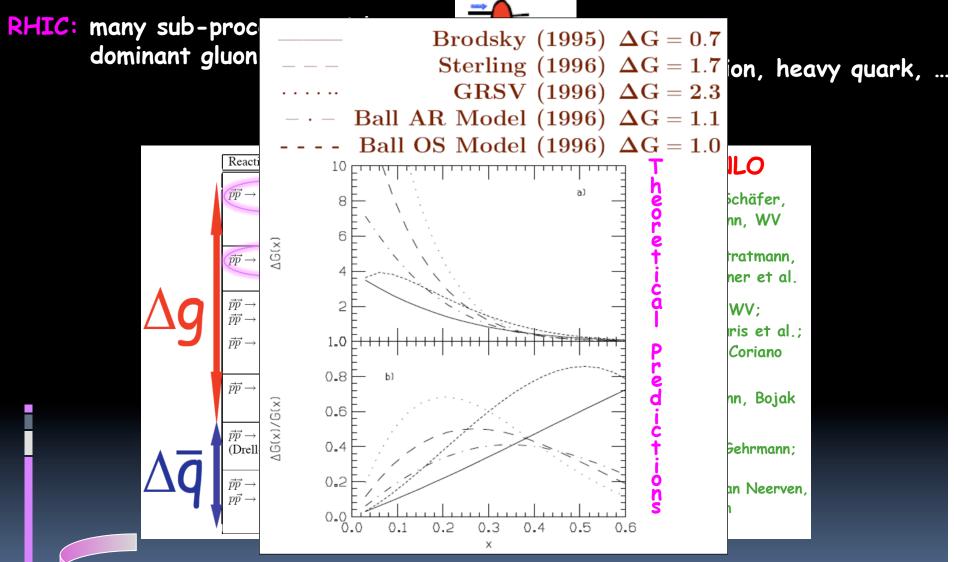
total u+d+s quark spin

gluon

angular momentum Where do we stand solving the "spin puzzle"?



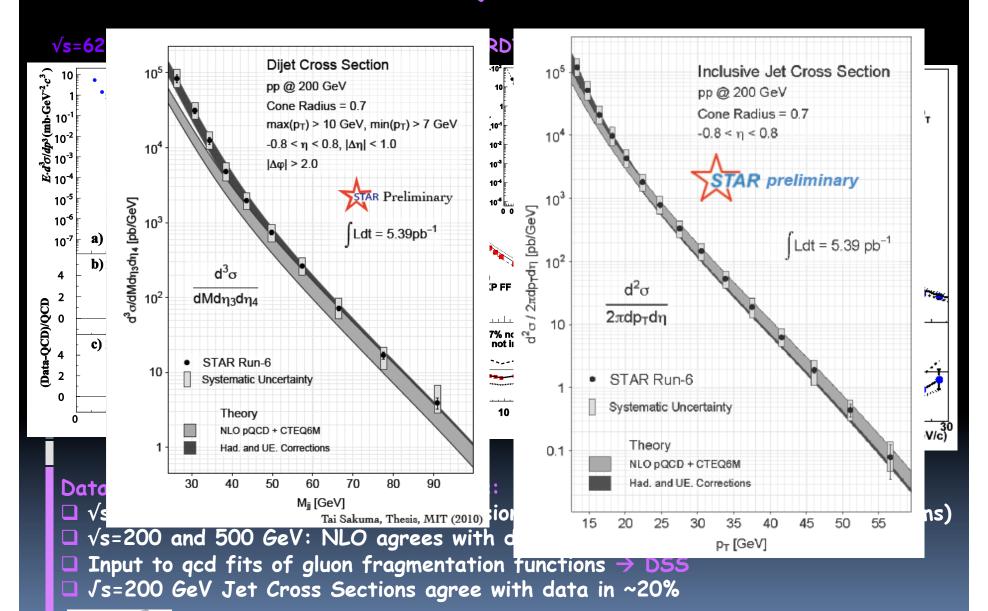
### The Gluon Polarization



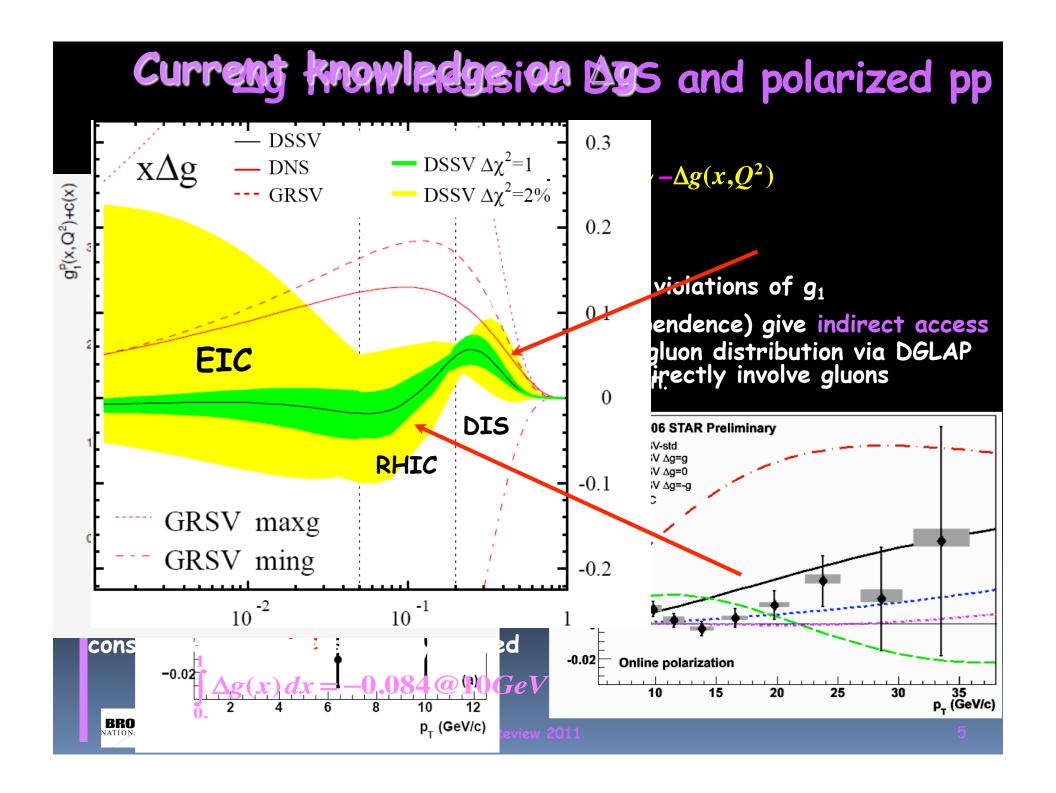
unpolarised cross sections nicely reproduced in NLO pQCD



### Does QCD work: Cross Sections



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### $\Delta g$ and the relevance of RHIC data

0.2

0.2

-0.2

-0.2

x-range: 0.05-0.2

DSSV- (DIS+SIDIS)-

 $\Delta g^{1, [0.05-0.2]}$ 

DSSV- (DIS+SIDIS)

x-range: 0.2-1.0

DSSV

SIDIS\*

 $\Delta g^{1, [0.05-0.2]}$ 

DSSV-

DIS SIDIS<sup>3</sup>

 $\Delta g^{1, [0.2-1.0]}$ 

--- DIS

DSSV+

 $\Delta \chi_i^2$ 

 $\Delta \chi_i^2$ 

10

10

0.2

0.2

truncated moment ("RHIC pp region")

DSSV: Phys.Rev.D80:034030,2009 DSSV+: DSSV+new DIS/SIDIS data

truncated moment ("high x")

- $\Delta g^{1,\,[\,0.2\text{-}1.0\,]}$  $\square$  RHIC pp data clearly needed (current DIS+SIDIS data alone do not constrain  $\triangle g$ )
- $\square$  new (SI)DIS data do not change much for  $\triangle g$

390

385

380

390

385

380

 $\chi^2$ 

-0.2

 $\Box$  trend for positive  $\Delta g$  at large x (as before)

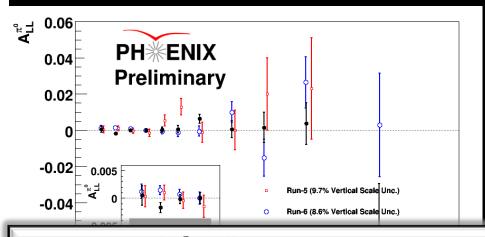


-0.2

#### bottom line:



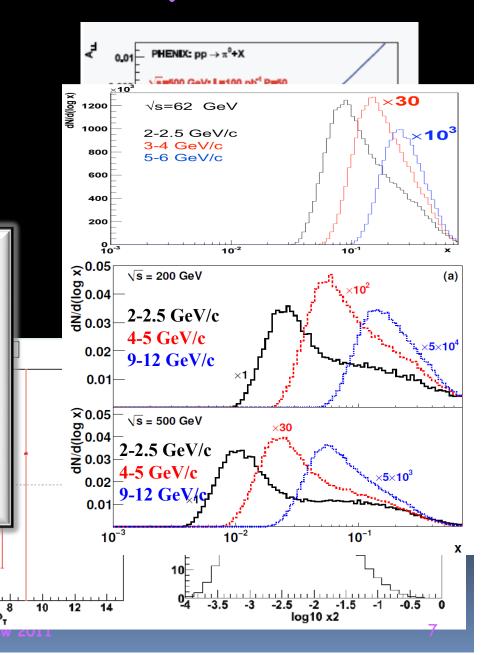
### Much more data on tape and to come



- □ Increased \( \square \) allows to go to lower \( \times \)
  □ Different final states select between
  - Different final states select between gg and qg scattering
  - → sign of \( \Delta g \)
- Future measurements will include di-hadron at forward rapidity
  - $\rightarrow$  constrain  $\times$  and to go to lower  $\times$

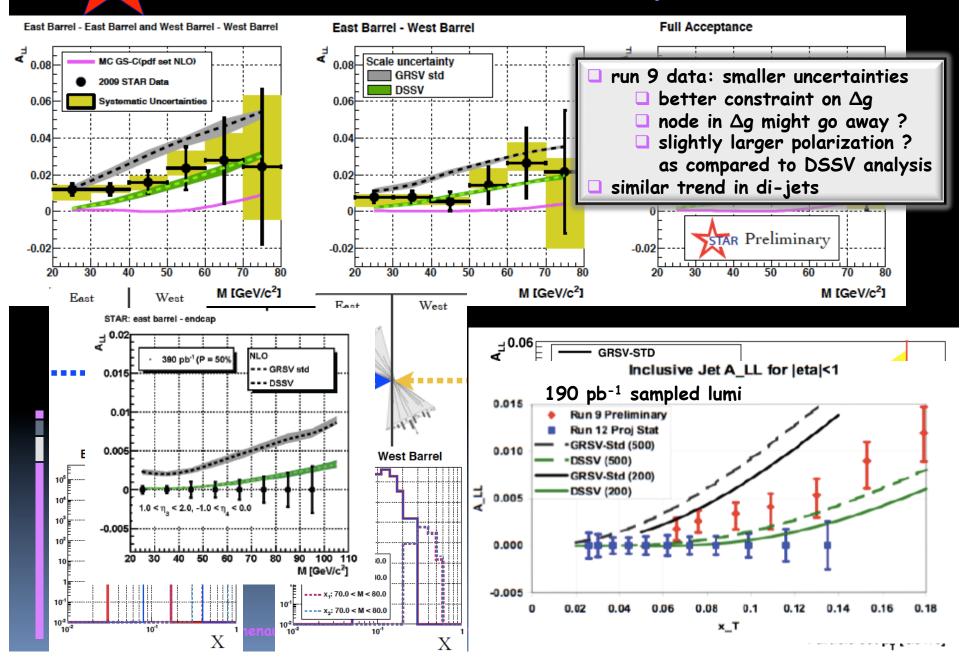
-0.002 3.1<η<3.8

challenge relative luminosity measurement





### STAR Much more data on tape and to come

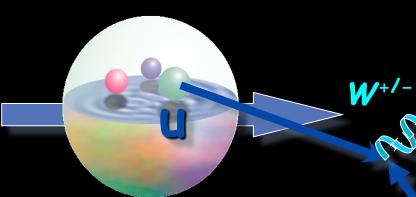


### Δq: W Production Basics

Since W is maximally parity violating

 $\rightarrow$  W's couple only to one parton helicity large  $\Delta u$  and  $\Delta d$  result in large asymmetries.





No Fragmentation!

$$u\overline{d} \rightarrow W^{+}$$

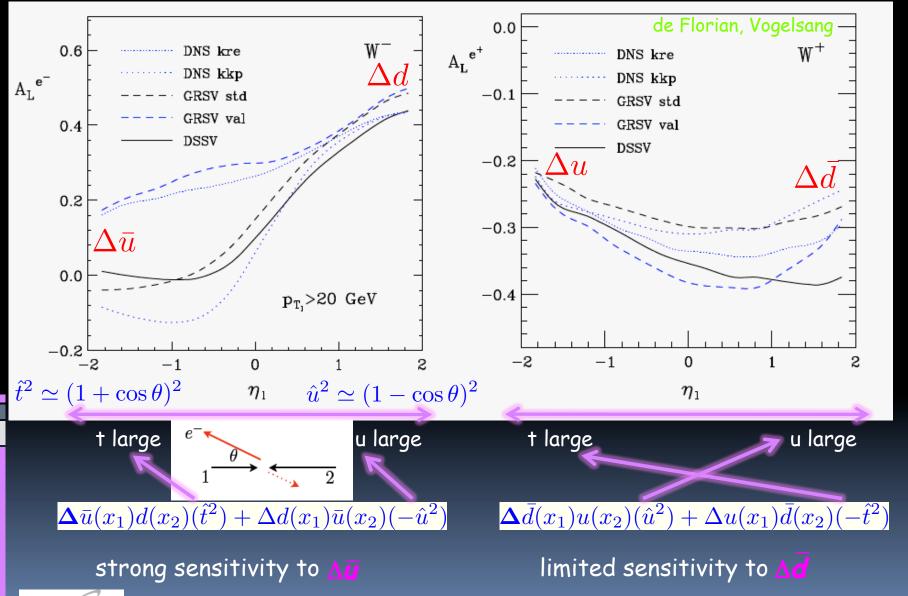
$$d\overline{u} \rightarrow W^-$$



$$A_{L}^{W^{+}} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim \frac{\Delta \overline{d}(x_{1})u(x_{2}) - \Delta u(x_{1})\overline{d}(x_{2})}{\overline{d}(x_{2})u(x_{1}) + \overline{d}(x_{1})u(x_{2})}$$

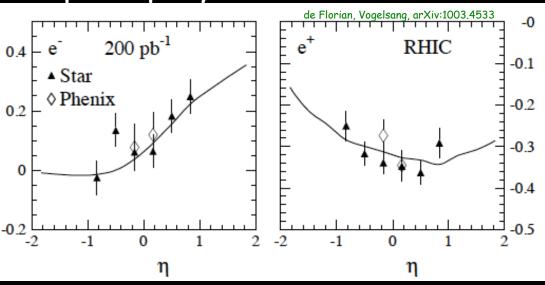
Similar expression for W to get  $\Delta \bar{\boldsymbol{u}}$  and  $\Delta d$ ...

### expectations for $A_{L}^{e}$ in pp collisions



### RHIC: A<sub>L</sub> for W bosons

□ RHIC: can detect only decay leptons; lepton rapidity most suited observable

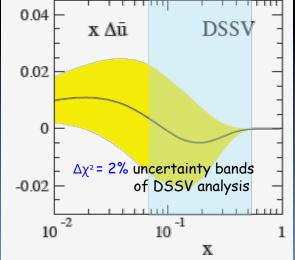


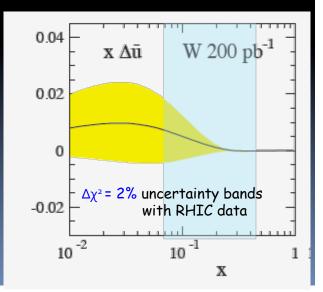
• strong correlation with  $x_{1,2}$ 

$$\langle x_{1,2} \rangle \sim \frac{M_W}{\sqrt{s}} e^{\pm \eta/2}$$

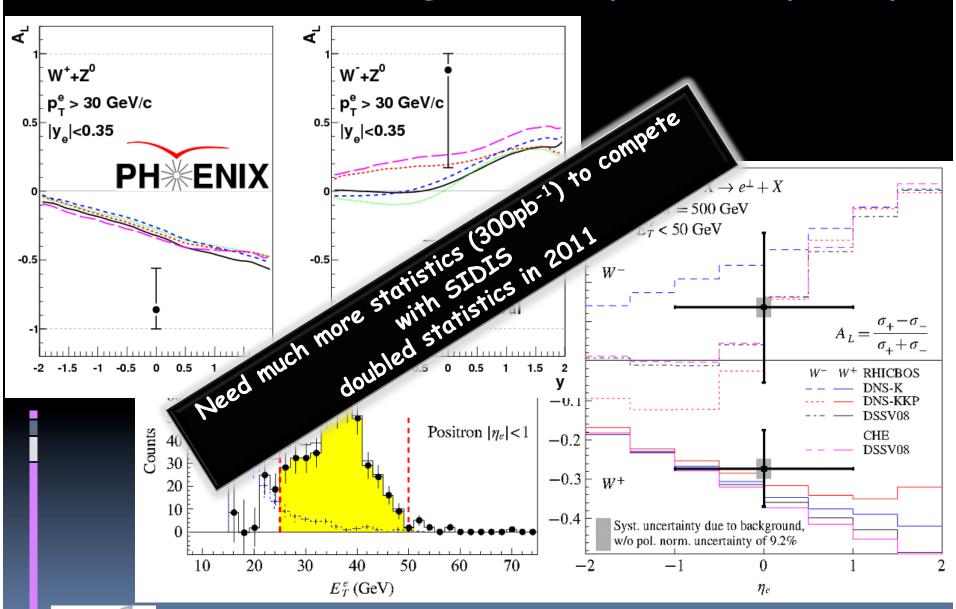
 $\square$  allows for flavor separation for 0.07 <  $\times$  < 0.04







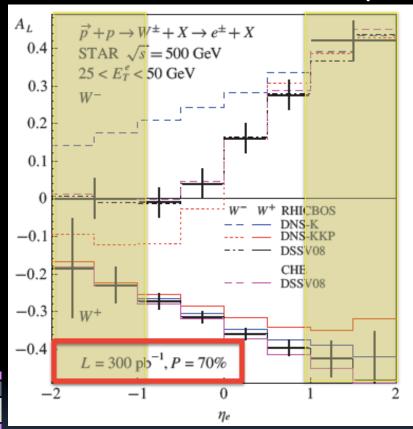


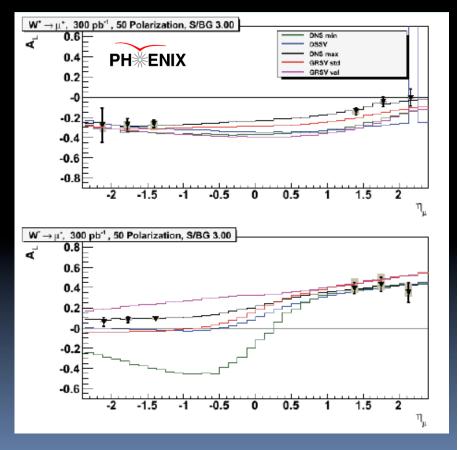


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### A<sub>L</sub><sup>W</sup>: Future Data

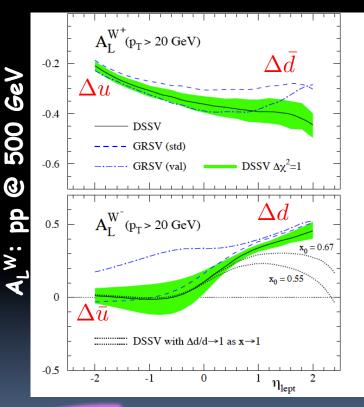
#### $\square$ will/have extend/extended rapidity from -1< $\eta$ <1 to -2< $\eta$ <2

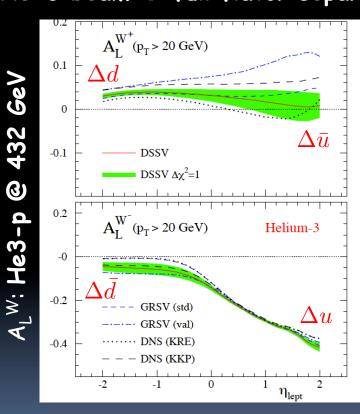




### A<sub>L</sub><sup>W</sup>: Future Possibilities

- Can we increase p-beam energy?
  - ♦ 325 GeV: factor 2 in  $\sigma_W$
  - lacktriangle access to lower x for  $\Delta g(x)$
- □ Increased beam-energy and polarized He-3 beam → full flavor separation





phase 2 of pp2pp@STAR can separate scattering on n or p



### Quantum phase-space tomography of the nucleon

Wigner Distribution  $W(x,r,k_t)$ 



Join the real 3D experience!!





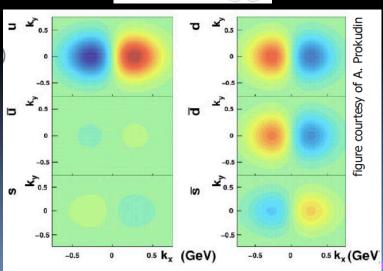


3D picture in momentum space transverse momentum dependent distributions

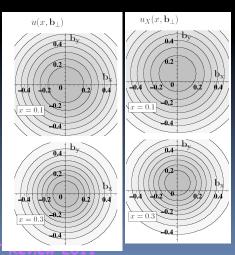
3D picture in coordinate space generalized parton distributions

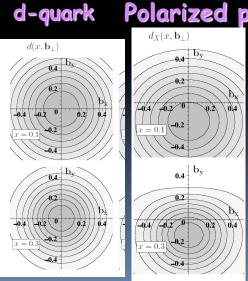
→ exclusive reaction like DVCS











### More insights to the proton - TMDs



Unpolarized distribution function q(x), G(x)



Transversity distribution function  $\delta q(x)$ Correlation between  $\vec{S}_{\perp}^{q}$  and  $\vec{S}_{\perp}^{N}$ 

> beyond collinear picture Explore spin orbit correlations



Helicity distribution function  $\Delta q(x)$ ,  $\Delta G(x)$ 





Boer-Mulders distribution function  $h_1^\perp$ Correlation between  $ec{s}_\perp^{\ q}$  and  $ec{k}_\perp^{\ q}$ 



chiral even naïve T-odd DF
related to parton orbital angular
momentum
violates naïve universality of PDFs
QCD-prediction:  $f^{\perp}_{1T,DY} = -f^{\perp}_{1T,DIS}$ 





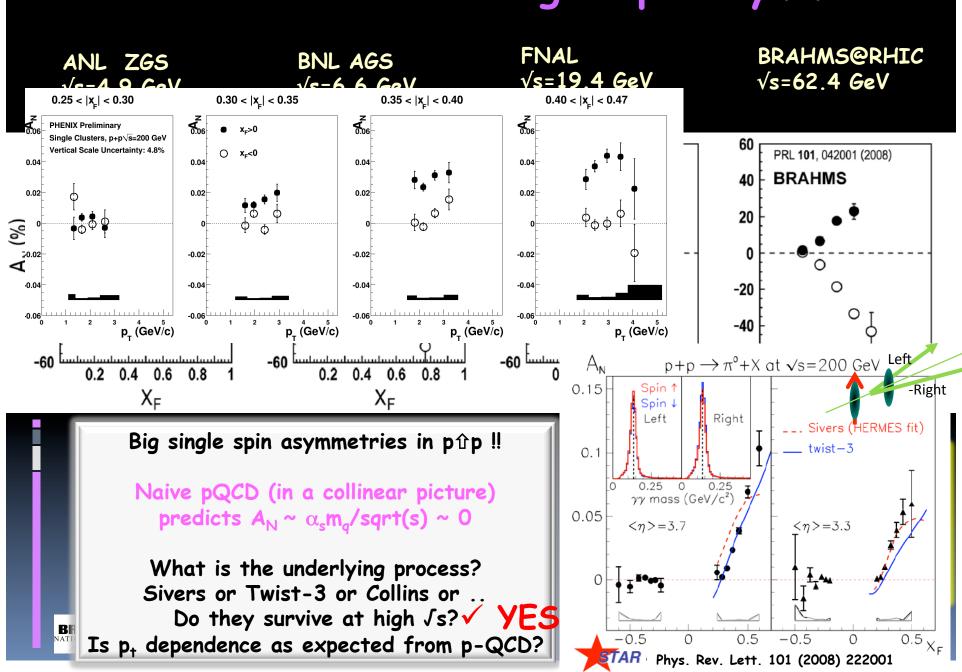
Sivers distribution function  $f_{1T}^{\perp}$ Correlation between  $\vec{S}_{\perp}^{N}$  and  $\vec{k}_{\perp}^{q}$ 



Asymmetries

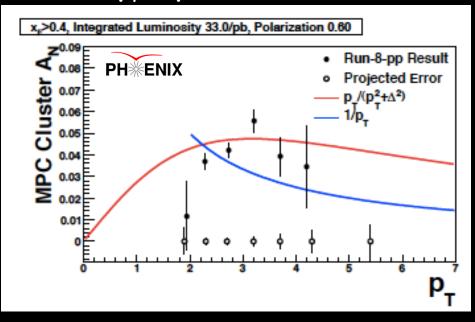
Sing-e

### Transverse single-spin asymmetries

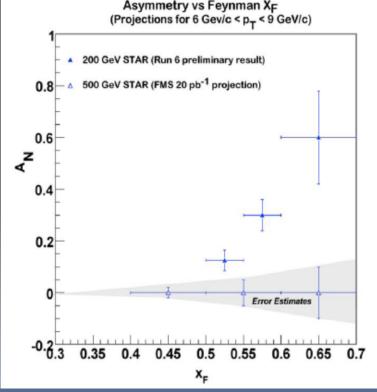


### Transverse single-spin asymmetries: Near Future

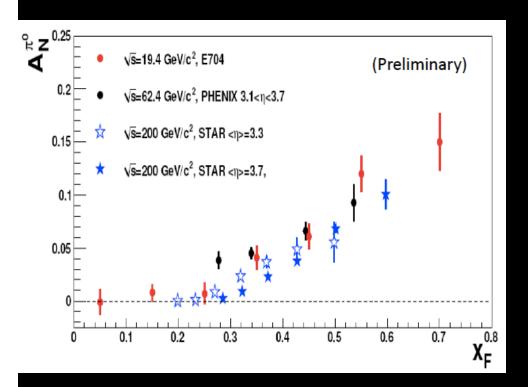
□ Test p<sub>t</sub> dependence

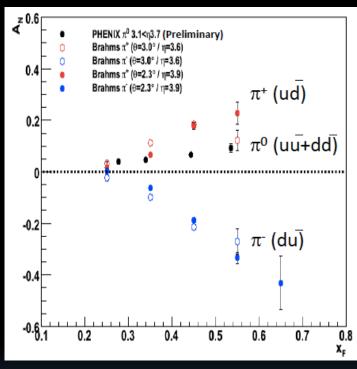






### What is seen at RHIC





No strong dependence on √s from 19.4 to 200 GeV

- $\checkmark$  Spread probably due to different acceptance in pseudorapidity and/or  $p_T$
- √ x<sub>F</sub> ~ ⟨z⟩P<sub>jet</sub>/P<sub>L</sub> ~ x : shape induced by shape of Collins/Sivers
- $\checkmark$  Sign also consistent with Sivers and/or Transversity x Collins

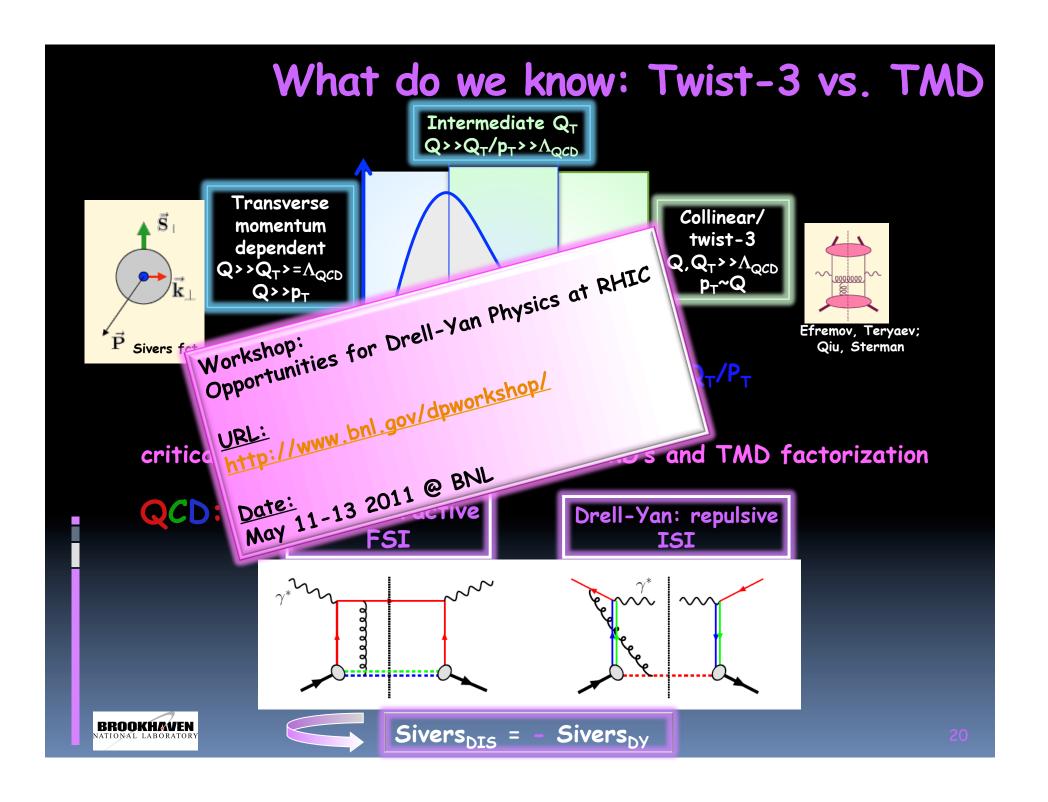
need other observables to disentangle underlying processes !!!!

Do we really understand the theory ???

E.C. Aschenauer

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RHIC S&T Review 2011



### from sign changes to sign mismatches

• latest twist: "sign mismatch" Kang, Qiu, Vogelsang, Yuan

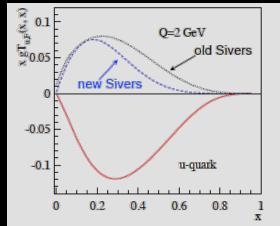
 $1^{st}$   $k_T$  moment of Sivers fct and twist-3 analogue related at operator level

$$gT_{q,F}(x,x) = -\int d^2k_{\perp} \frac{|k_{\perp}|^2}{M}$$

Boer, Mulders, Pijlman; Ji, Qiu,, Vogelsang, Yuan

both sides have been extracted from data find: similar magnitude √but wrong sign ₩

inconsistency in formalism?



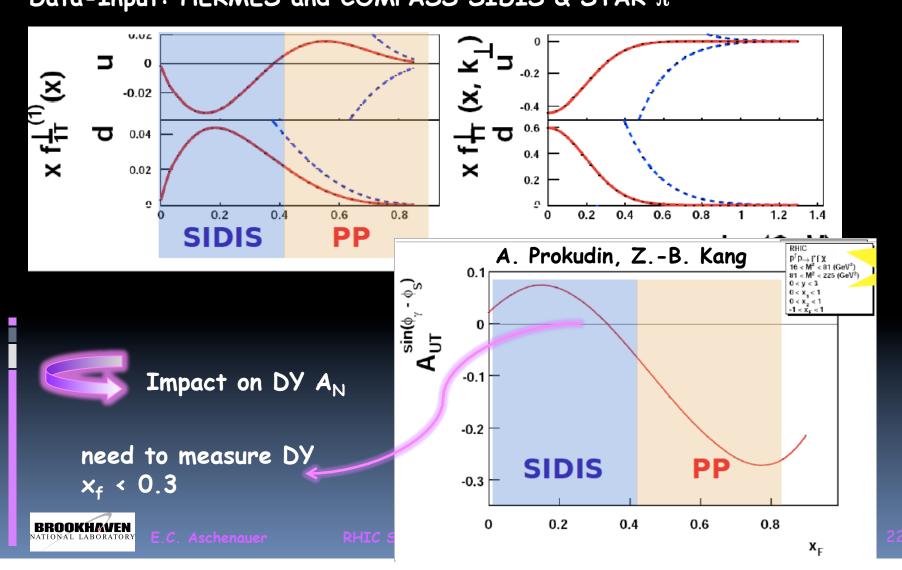
- possible resolutions: (1) data constrain Sivers fct only at low  $k_T$ ; function has a node phenomenological studies with more flexible Sivers fct. under way

  Kang, Prokudin
  - (2) analysis of  $T_{q,F}$  neglects possible final-state contributions to  $A_N$  need data for  $A_N$  which are insensitive to fragmentation: photons, jets, DY
- on the bright side: recent progress on evolution for Sivers fct Kang, Xiao, Yuan crucial for consistent phenomenology properly related experiments at different scales

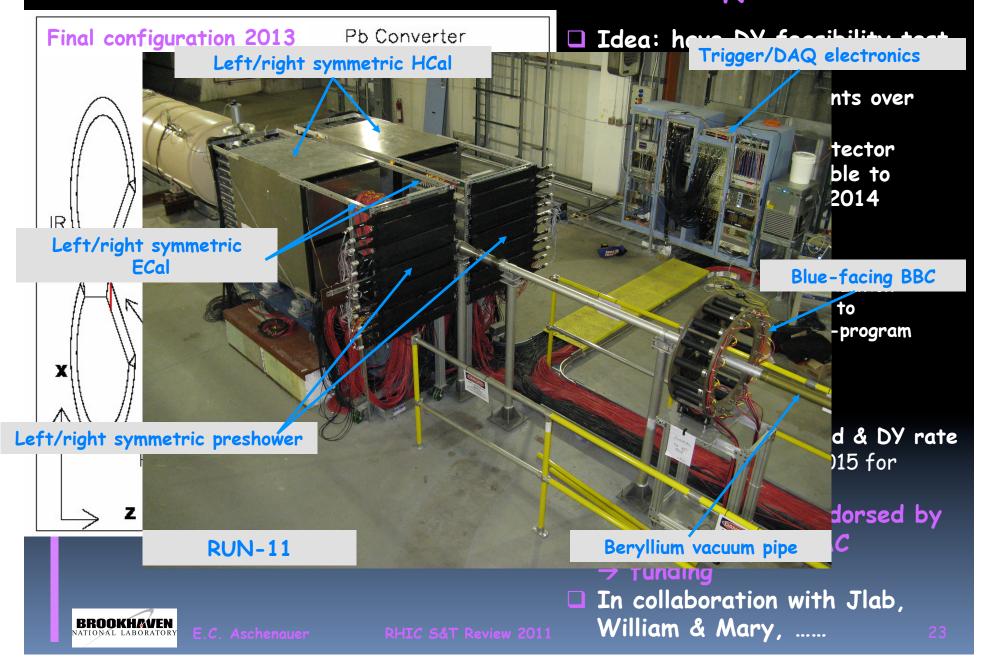
### New Global Fit

#### Parameterization:

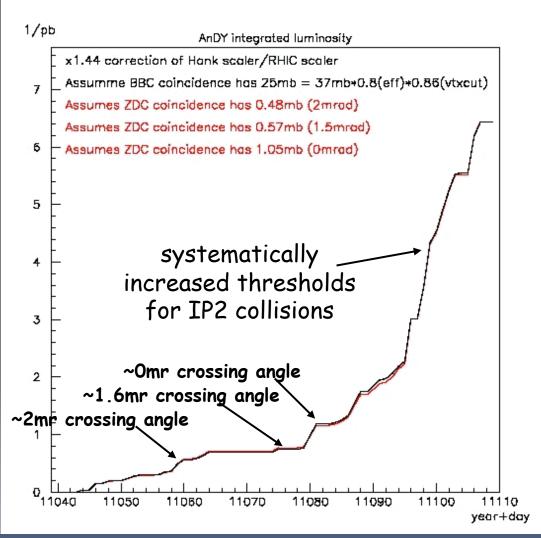
 $f_{1T}^{\perp q} \sim \chi^{\alpha_q} (1-\chi)^{\beta_q} (1-\eta_q \chi)$  shape ala DSSV node if  $\eta_q > 0$  Data-Input: HERMES and COMPASS SIDIS & STAR  $\pi^0$ 



### ANDY @ IP-2



### Run11 Goal (1) - 3IR impact



Fri. 8 April

IP2 collisions have begun <3 hours after physics at 1.50×10<sup>11</sup>/bunch

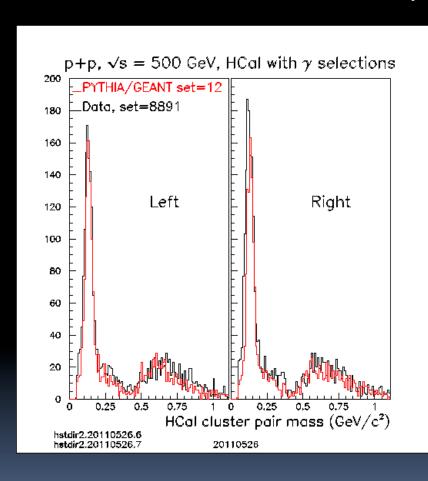
 $A_N$ DY got ~ 6.5/pb in run11 with  $\beta$ \*=3m





### Run11 Goal (2) - HCal calibration

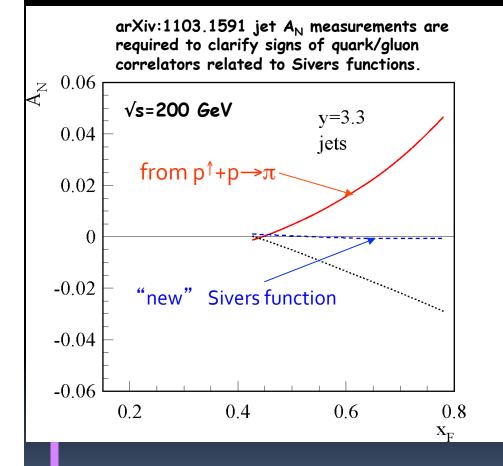
### HCal without ECal in front = $\pi^0$ in Hcal



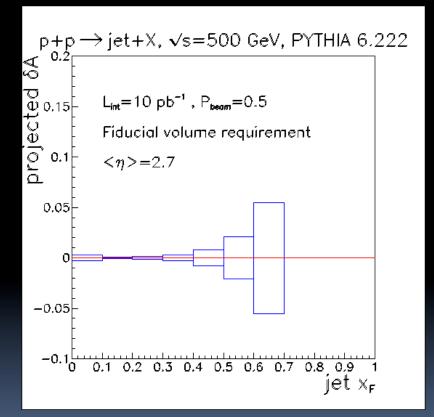
- □ 20M BBC collision data and 20M simulations events (PYTHIA+GEANT)
- Requirements:
  - (1) 1-tower clusters;
  - (2) E>1.8 GeV;
  - (3) |x| > 50 cm to avoid ECal shadow;
  - (4) >1 clusters to form pairs;
  - (5) E<sub>pair</sub> > 5 GeV;
- (6)  $M_{pair}^{color}$  <0.5 GeV; and (7)  $z_{pair}$  <0.5. Hadronic response also under study with prospects for  $\rho^{\pm} \rightarrow \pi^{\pm} \pi^{0}$  and  $\omega \rightarrow \pi^+\pi^-\pi^0$  to correct h/ $\gamma$  differences



### Run11 Goal (3): $A_N$ for jets



□ With ~10/pb & P=50%,  $A_N$ DY run11 can measure  $A_N$ (Jet).



Determine whether  $A_N(jet)$  is non-0 is a requirement for  $A_N(DY)$  sign-flip measurement



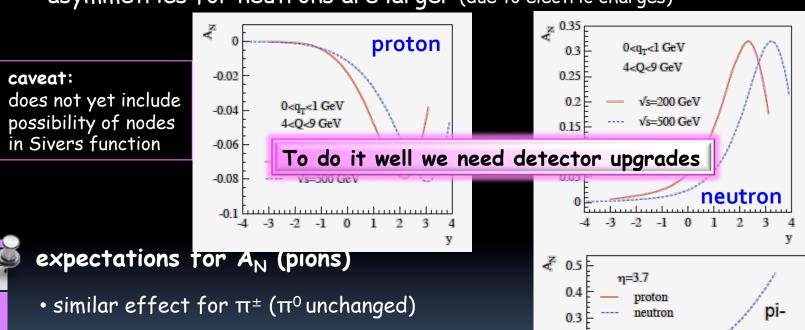
### The long term future future of pp@RHIC

A<sub>N</sub> in <sup>3</sup>He-proton collisions

BROD

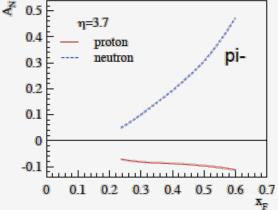
Sivers fcts. for u and d quarks opposite in sign and slightly larger for d quarks expectations for Drell Yan Z. Kang @ 2010 Iowa RSC meeting

- u <-> d isospin rotation leads to different signs for  $A_N$  for protons and neutrons
- asymmetries for neutrons are larger (due to electric charges)

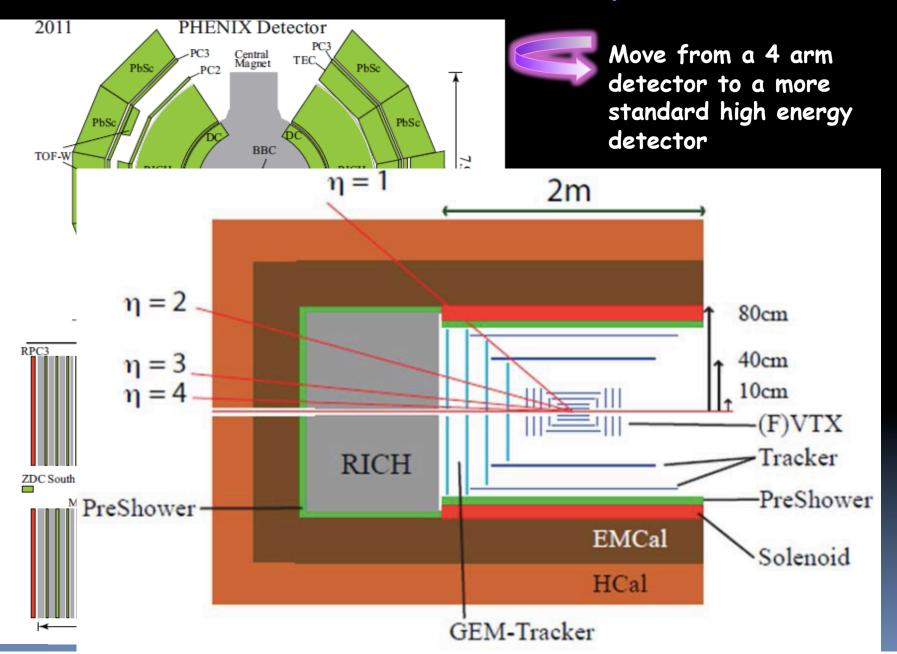


this time computed within twist-3 formalism

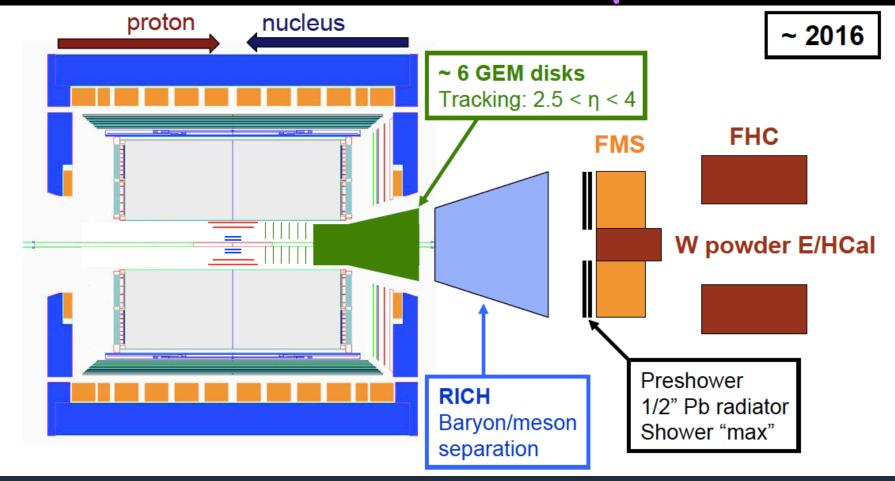
here, effect due to favored/unfavored fragmentation



### Detector Developments: PHENIX



### Detector Developments: STAR

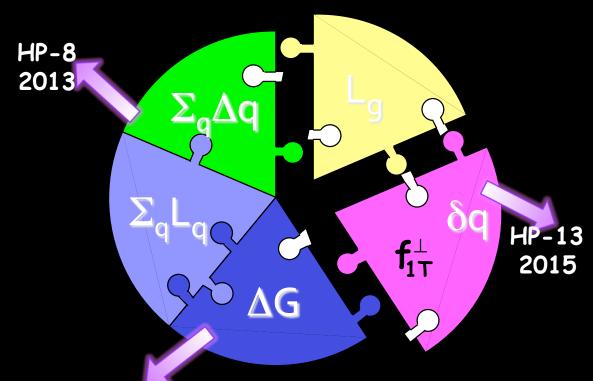


Forward instrumentation optimized for p+A and transverse spin physics

- √Charged-particle tracking
- $\checkmark$  e/h and  $\gamma/\pi^0$  discrimination
- ✓Baryon/meson separation



### Summary: RHIC Spin Program



HP-12 2013

Active program with many new developments in theory and experiments

On track to achieve mile-stones



### THE RHIC SPIN GROUP



### News from the Group

- Changes in group personnel
  - ◆ Dr. Gerry Bunce retired in 2008
    - E.C. Aschenauer replaced Dr. Bunce in March 2009
  - Dr. R. Gill left the group, because he became the full time safety officer for Daya Bay and LBNE
  - ◆ Dr. B. Morozov will left the group 30th of June 2010
    - Dr. Morozov was be replaced in October 2010 by Dr. W. Schmidke from ZEUS@DESY (tenure track)
    - The new tenure candidate concentrates on operating the polarimeters, to further develop
      - Current size of the group:
        - 4 PostDocs (2 DOE & 2 Director funds)
  - Dr. A. (5 physicists (3 tenured and 2 continuing appointment)
    - job 1 tenure track scientist

rt to interview

- Hired two PostDocs D. Smirnov from DO@Fermilab and Alan Dion from PHENIX@BNL to work on polarimetry and physics analysis
  - they joined the group in August and September 2010
  - both postdocs are involved in the core spin physics program of STAR
- Dr. Th. Burton (Dec 09) and Dr. S. Fazio (Jul. 10) hired as Postdocs for EIC (75%) and RHIC Spin (25% STAR-spin)
  - both PostDocs are funded from BNL laboratory development funds
- ♦ Hire one more postdoc from LDRD funds for Si-Pixel R&D



### The RHIC SPIN Group







**Polarimetry** 



Les Bland Akio Ogawa Wlodzimierz Guryn Elke-C. Aschenauer Alexander Bazilevsky

Elke-C. Aschenauer Alexander Bazilevsky Les Bland Akio Ogawa

Elke-C. Aschenauer Alexander Bazilevsky

Since 2010/2011 Alan Dion William B. Schmidke Dimitri Smirnov

Elke-C. Aschenauer Thomas P Burton Salvatore Fazio Wlodzimierz Guryn new LDRD-postdoc for Si-pixel R&D

Since 2010/2011 Thomas P Burton Alan Dion Salvatore Fazio William B. Schmidke Dimitri Smirnov

Hardware responsibilities BBC, FMS-Calib.

Roman Pots of pp2pp

#### Physics goals:

Forward Physics in dAu luon saturation → CGC

Single Spin Asymmetries  $A_N \rightarrow Jet, W, Di-jet$ 

pp2pp: diffractive physics & glueball searches Physics goals:

 $\Delta G$  & cross section via  $\pi^0$ ,  $A_NDY$ 

A<sub>L</sub> W-physics Drell-Yan in pp

AB (>2005) & ECA (>2009) Organizing the RSC meetinas A. Bazilevsky:

Trigger coordinator Run1

Hardware responsibilities:

Design, Setup, commissioning and running Hardware responsibilities:

Physics goals:

Measure sign change for the Sivers fct. between DIS and DY

Develop requirements for DY measurements Star & PheniX for pp and dAu

pC polarimeters, H-Jet detectors Improvements of the Polarimeters

DAQ

Physics goals: Offline analysis of polarimeter data → final polarization

Feedback to CAD to improve polarization in RHIC

>for experiments

Responsibilities:

Detector Design and IR integration hadron polarimetry "Roman Pots" Software tools

Physics goals:

Develop physics case for ep (pol/unpol)

ECA Co-convener of the BNL EIC-TF

ECA:

decadal plan: spin physics and

forward arm new detector

**ePHENIX** 

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· Postdocs: funded by LDRDs and Director's Funds

RHIC S&T Review 2011 · Postdocs: funded by DOE ME

### Group Achievements

- □ Promotions:
  - ◆ Dr. A. Bazilevsky received tenure in 2009
  - ◆ Dr. A. Ogawa received a continuing appointment in 2009
  - ◆ Dr. E.C Aschenauer received tenure in 2010
- □ Papers:
  - ◆ STAR:
    - 1 paper on polarized pp (10 citations)
  - PheniX:
    - 6 total papers on polarized pp (34 citations)
    - 1 with contributions from the RHIC Spin Group
  - ◆ Papers not on RHIC
    - 1 Belle; 13 HERMES
- □ ~57 Seminars and Presentations on Conferences and Workshops

### RHIC SPIN GROUP PHYSICS HIGHLIGHTS

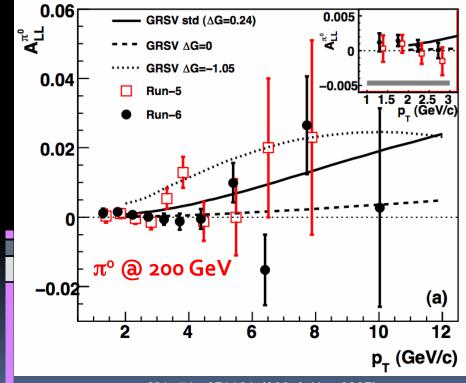


## The PHNENIX π<sup>0</sup> ALL

#### Analysis done by/under the leader ship of S. Bazilevsky

$$A_{LL} = \frac{1}{P_B P_Y} \frac{N^{++} - \frac{L^{++}}{L^{+-}} N^{+-}}{N^{++} + \frac{L^{++}}{L^{+-}} N^{+-}} \sim a_{gg} \Delta g^2 + b_{gq} \Delta g \Delta q + c_{qq} \Delta q^2$$

$$\frac{\Delta G}{G} \frac{\Delta G}{G} \qquad \frac{\Delta q}{q} \frac{\Delta G}{G} \qquad \frac{\Delta q}{q} \frac{\Delta q}{q} \qquad + \dots$$

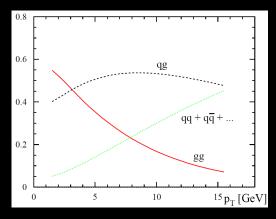


PRD 76, 051106 (200 GeV - 2005) PRL 103, 12003 (200 GeV - 2006) PRD 79, 012003 (62 GeV - 2006)

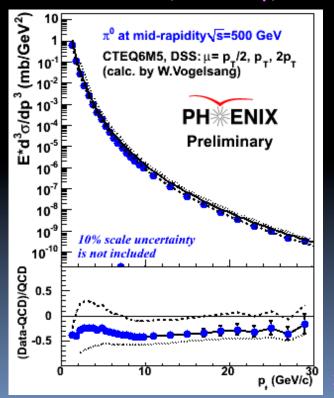
E.C. Aschenauer

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RHIC S&T Review 2011

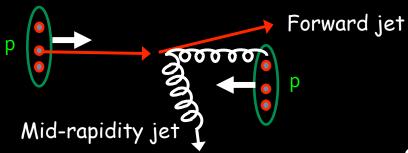


#### $\sqrt{s}=500 \text{ GeV (Preliminary)}$



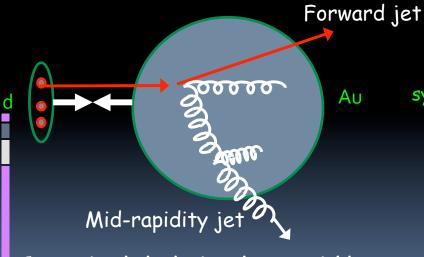
### Signature for gluon saturation: di-hadron correlation

pQCD 2-2 process = back-to-back di-jet: (Works well for p+p)

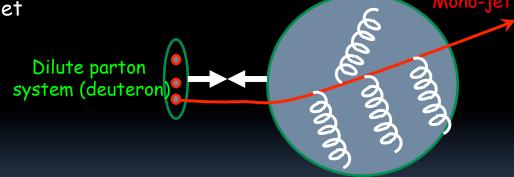


Saturation / CGC 2 $\rightarrow$ 1 (or 2 $\rightarrow$ many or 1 $\rightarrow$ many) process = Mono-jet

#### pQCD + shadowing:



Conventional shadowing changes yield, but not angular correlation

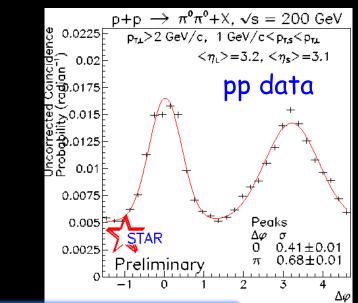


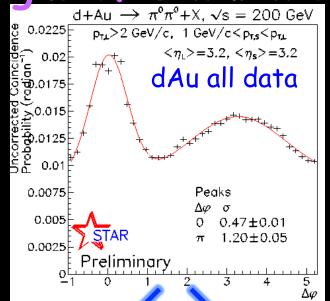
#### Dense gluonfield (Au)

P<sub>T</sub> is not balanced by one parton, but something else (many gluons?) CGC predicts suppression of back-to-back correlation



### RHIC: Signs of Saturation in dAu





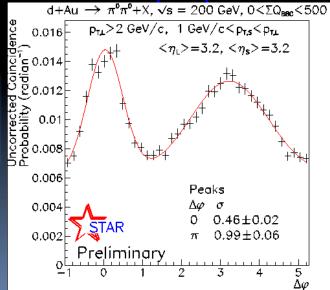
Analysis done by L. Bland, A. Gordon & A. Ogawa

Away-side peaks evident in peripheral dAu and pp.

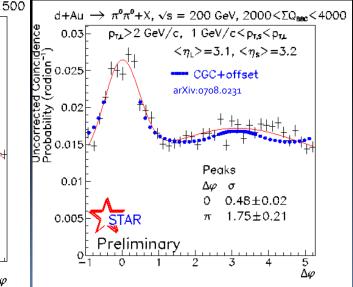
Near side peaks unchanged in dAu for peripheral to central.

Azimuthal decorrelations show significant dependence on centrality.

#### dAu peripheral



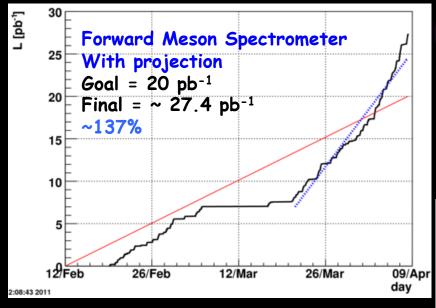
#### dAu Centra

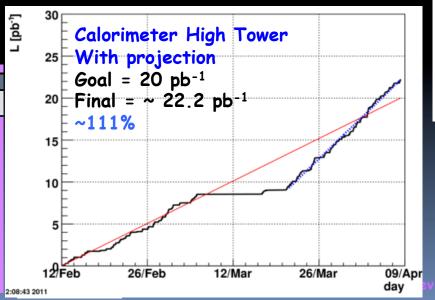


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# STAR: Upcoming physics topics

Sampled Luminosity for STAR FY11 pp 500 Transverse data set







Nice data set to study

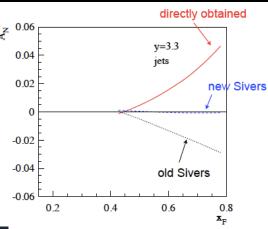
A<sub>N</sub> - jet: → Sivers fct.

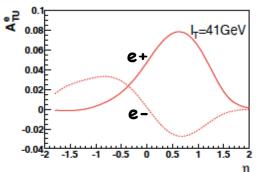
A<sub>N</sub> for single lepton from W<sup>+/-</sup>:

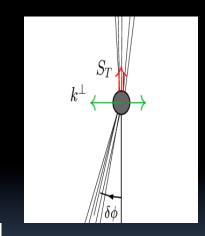
Sign change in Sivers fct. compared to SIDIS

A<sub>N</sub> for dijets: Sivers fct. via back to back

imbalance of 2 jets







Analysis to be done by:

Thomas P Burton Alan Dion Salvatore Fazio William B. Schmidke Dimitri Smirnov

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### eRHIC involvement of the group

- □ The members of the group have been major players in the 2010 EIC INT program
  - simulation of pseudo-data for impact plots for the golden measurements
    - → DG, TMDs, GPDs
  - developed MC and root tools for the studies, i.e. TMD-MC, GPD-MC
  - provide detector acceptance studies
  - **.....**





### Quantum phase-space tomography of the nucleon

Wigner Distribution  $W(x,r,k_t)$ 



Join the real 3D experience!!





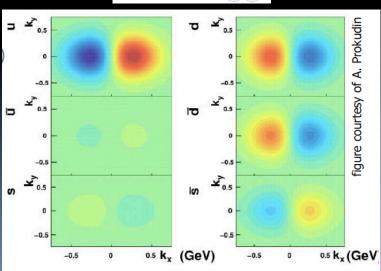


3D picture in momentum space transverse momentum dependent distributions

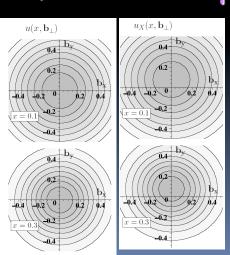
3D picture in coordinate space generalized parton distributions

→ exclusive reaction like DVCS

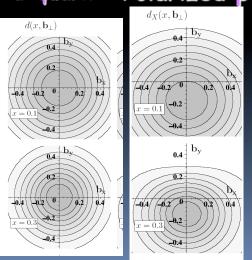




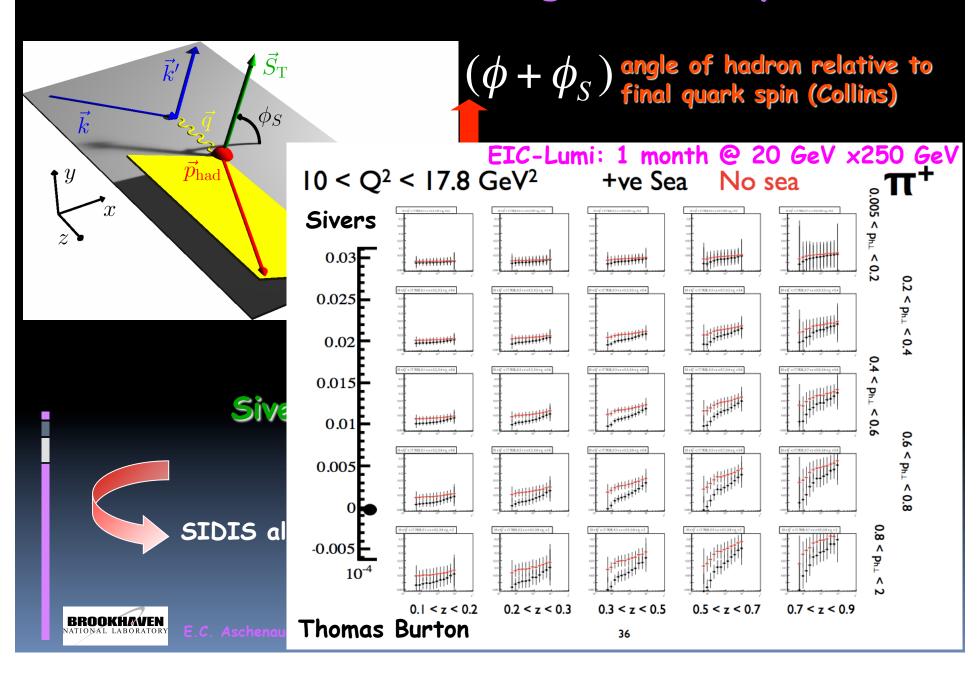




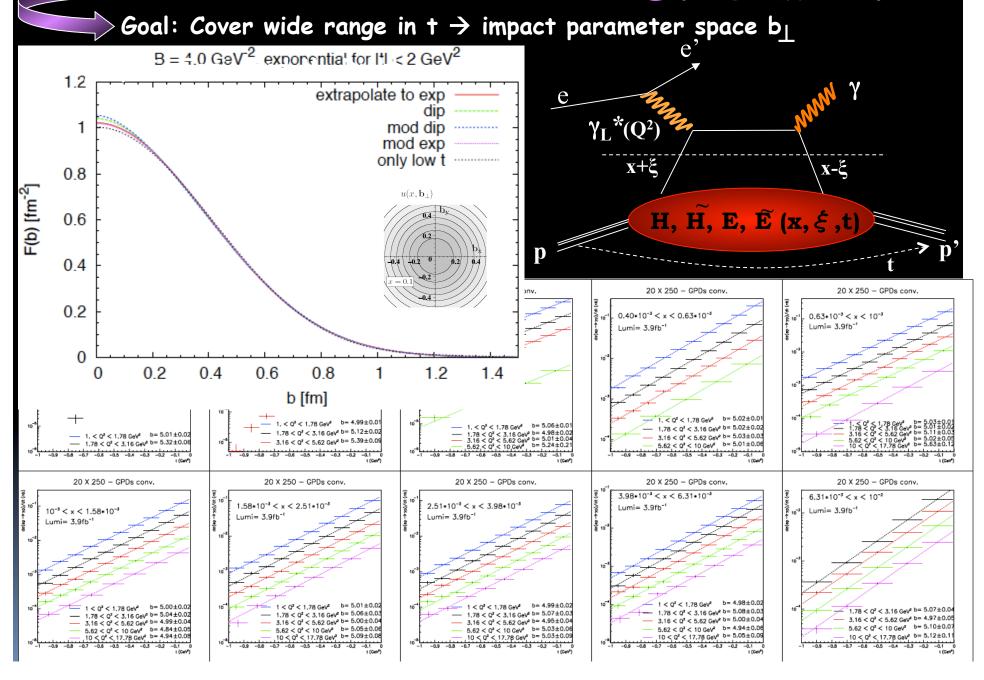
#### d-quark Polarized



### Azimuthal angles and asymmetries

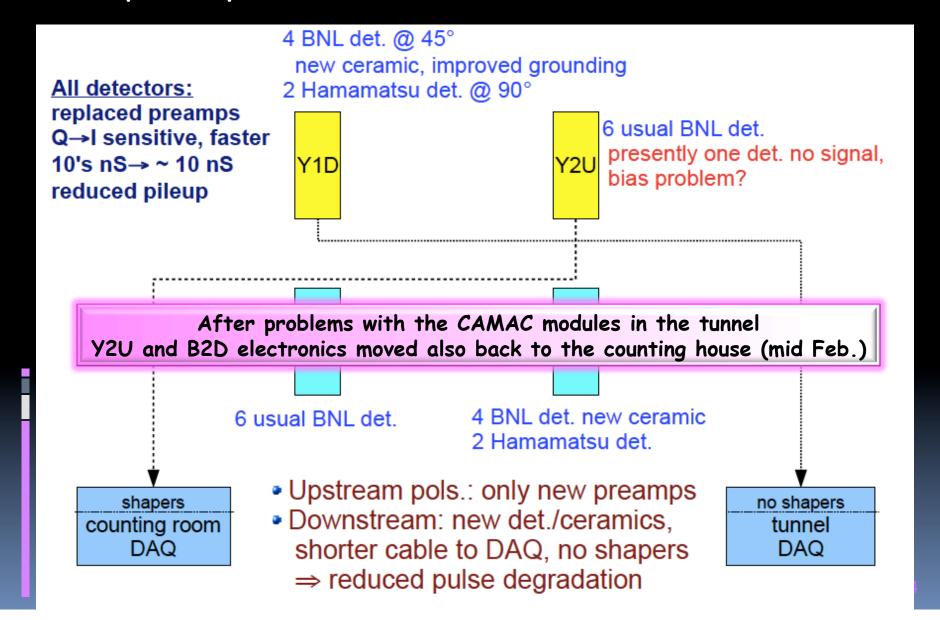


### DVCS at eRHIC



### Last but not least: RHIC Polarimetry

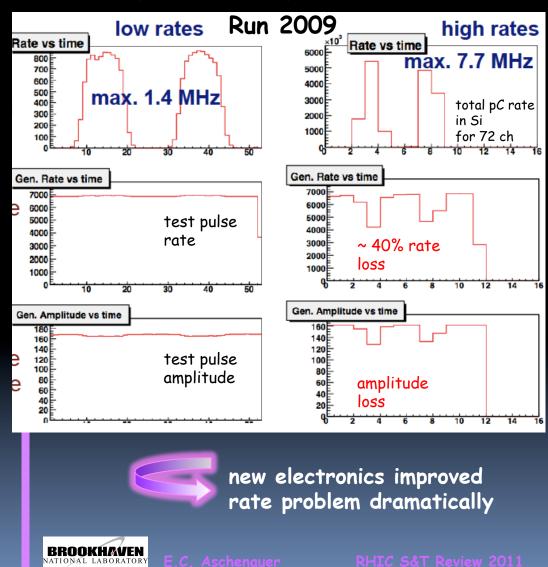
RHIC pC Setup Run-11

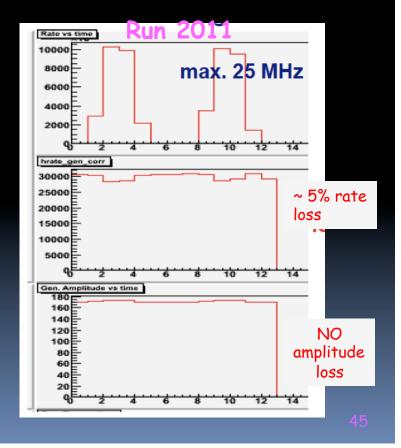


### RHIC pC Results: Rate effects

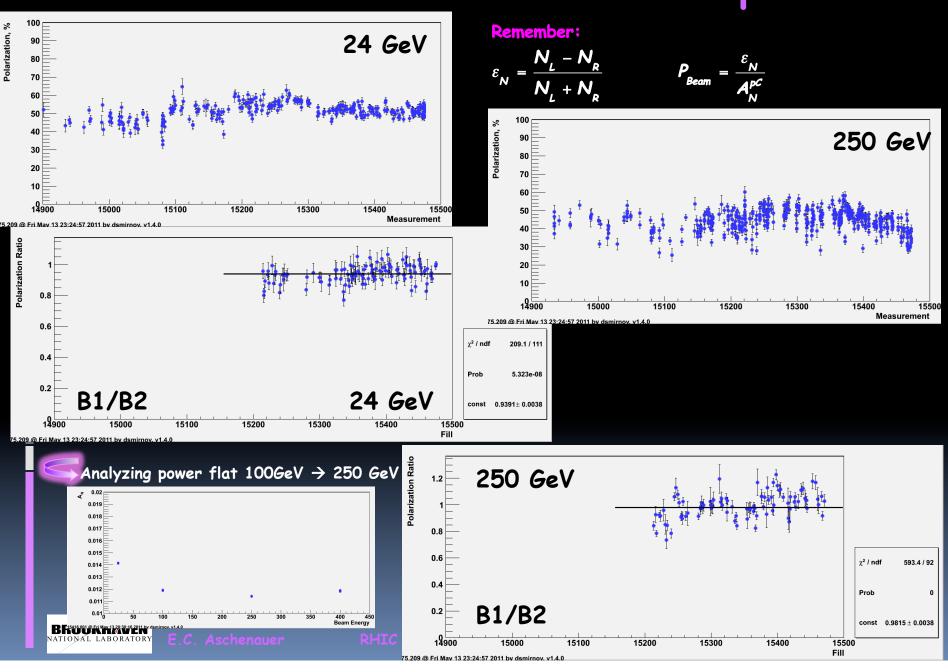
#### Rate effects:

- □ Test pulse applied to all preamps ~500 Hz
- Monitor pulse rate, amplitude for rate effects:



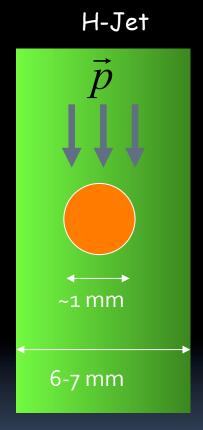


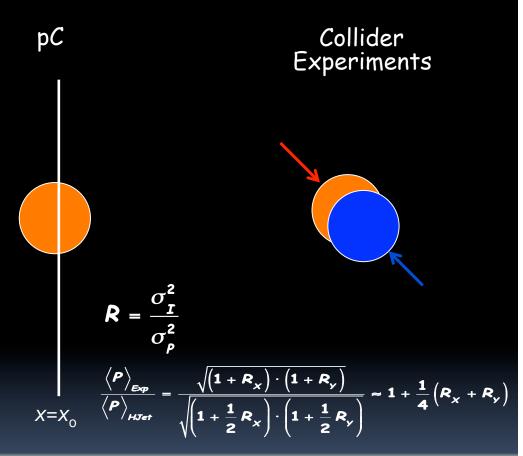
# RHIC pC Results



## RHIC pC Results: Polarization Profile

If polarization changes across the beam, the average polarization seen by Polarimeters and Experiments (in beam collision) is different



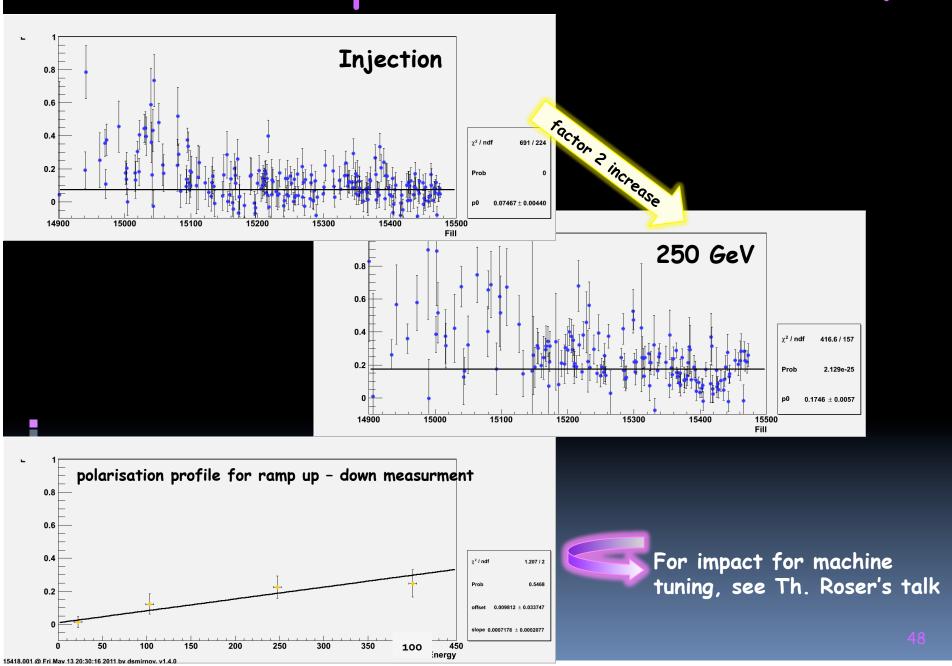


$$\langle P_1 \rangle = P_1(x, y) \otimes I_1(x, y)$$
  $\langle P_1 \rangle = P_1(x_0, y) \otimes I_1(x_0, y)$   $\langle P_1 \rangle = P_1(x, y) \otimes I_1(x, y) \otimes I_2(x, y)$ 

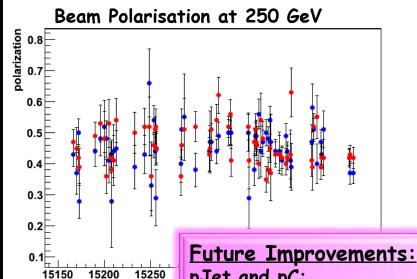
 $P_{1,2}(x,y)$  - polarization profile,  $I_{1,2}(x,y)$  - intensity profile, for beam #1 and #2

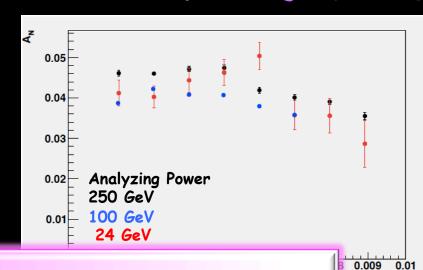






#### RHIC Jet Results





pJet and pC:

- > move to commercial Si detectors from Hamamatsu
  - > better E-resolution, cheaper, off the shelf
- > move to commercial VME based readout electronics
- → improve online analysis code and make it identical to offline pC:
- → main theme for future work improve stability
  - → improve in-situ calibration closer to C dE/dx
  - > better targets: movement and thickness stability
  - > measure to for ToF independent from Si-det.

#### pJet:

> preventative maintenance and increase stability

n at injection:

)48

mber:

-t [(GeV/c)2]

$$\frac{1}{P}\frac{N_L - N_R}{N_L + N_R} = \frac{\varepsilon}{P}$$

Beam Polar

0.52 0.52 0.52

0.48

0.44

0.42

0.4

0.38

### Summary

#### □ Last 5 years:

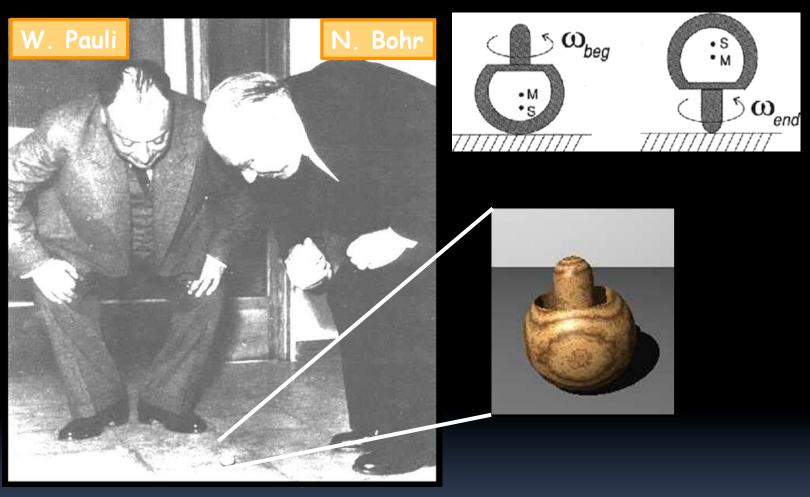
- ◆ BNL RHIC Spin Group was leading the effort on
  - $lack \Delta g$  in PheniX
  - forward physics @ STAR
    - transverse spin physics
  - RHIC Polarimetry together with CAD

#### □ Next 5 (++) years:

- will concentrate on
  - core transverse program of RHIC spin program in STAR (HP13)
  - develop a DY program for RHIC
    - √ to measure the sign change for the Sivers fct. in SIDIS and DY (HP-13)
    - ✓ evaluate the possibility of quark distributions in dAu
    - ✓ determine the requirements for discussed future forward upgrades in STAR & PheniX
       → next decadal plan
  - work on the physics case for eRHIC
    - → TMDs, GPDs, helicity distributions
    - ⇒ possibilities for ep/eA collisions in PheniX and STAR
    - ♦ detector and IR design for eRHIC
  - RHIC Polarimetry



# Spin is fascinating



Thank you for your attention



# BACKUP



# Collected Luminosity with longitudinal Polarization

Year	√s [GeV]	Recorded PHENIX	Recorded STAR	Pol [%]
2002 (Run 2)	200	/	0.3 pb <sup>-1</sup>	15
2003 (Run 3)	200	0.35 pb <sup>-1</sup>	0.3 pb <sup>-1</sup>	27
2004 (Run 4)	200	0.12 pb <sup>-1</sup>	0.4 pb <sup>-1</sup>	40
2005 (Run 5)	200	3.4 pb <sup>-1</sup>	3.1 pb <sup>-1</sup>	49
2006 (Run 6)	200	7.5 pb <sup>-1</sup>	6.8 pb <sup>-1</sup>	57
2006 (Run 6)	62.4	0.08 pb <sup>-1</sup>		48
2009 (Run9)	500	14 pb <sup>-1</sup>	10 pb <sup>-1</sup>	39
2009 (Run9)	200	16 pb <sup>-1</sup>	25 pb <sup>-1</sup>	55
2011 (Run11)	500	27.5 / 9.5pb <sup>-1</sup>	12 pb <sup>-1</sup>	~50%



# Collected Luminosity with transverse Polarization

Year	√s [GeV]	Recorded PHENIX	Recorded STAR	Pol [%]
2001 (Run 2)	200	0.15 pb <sup>-1</sup>	0.15 pb <sup>-1</sup>	15
2003 (Run 3)	200	/	0.25 pb <sup>-1</sup>	30
2005 (Run 5)	200	0.16 pb <sup>-1</sup>	0.1 pb <sup>-1</sup>	47
2006 (Run 6)	200	2.7 pb <sup>-1</sup>	8.5 pb <sup>-1</sup>	57
2006 (Run 6)	62.4	0.02 pb <sup>-1</sup>		53
2008 (Run8)	200	5.2 pb <sup>-1</sup>	7.8 pb <sup>-1</sup>	45
2011 (Run11)	500	/	25 pb <sup>-1</sup>	~50



#### discussion - pros and cons

#### pros



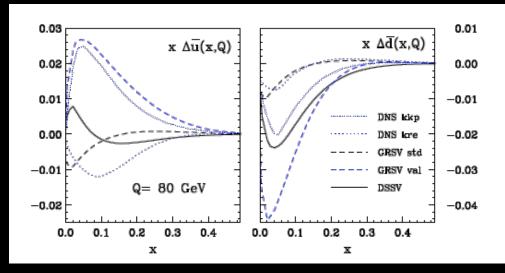
polarized He-3 mainly a neutron target:  $0.865 \, \text{n} + 2*(-0.027) \, \text{p}$ 

⇒important information for flavor separation complementary to pp

 $\Delta u, \Delta \bar{u} \leftrightarrow \Delta d, \Delta d$ 



cross section enhanced (nuclear "target")



#### cons



need maximum possible c.m.s. energy: 216 GeV protons on 216 GeV/n He-3 (feasible? - otherwise W cross section too small)



unpolarized He-3 a combination of p and n



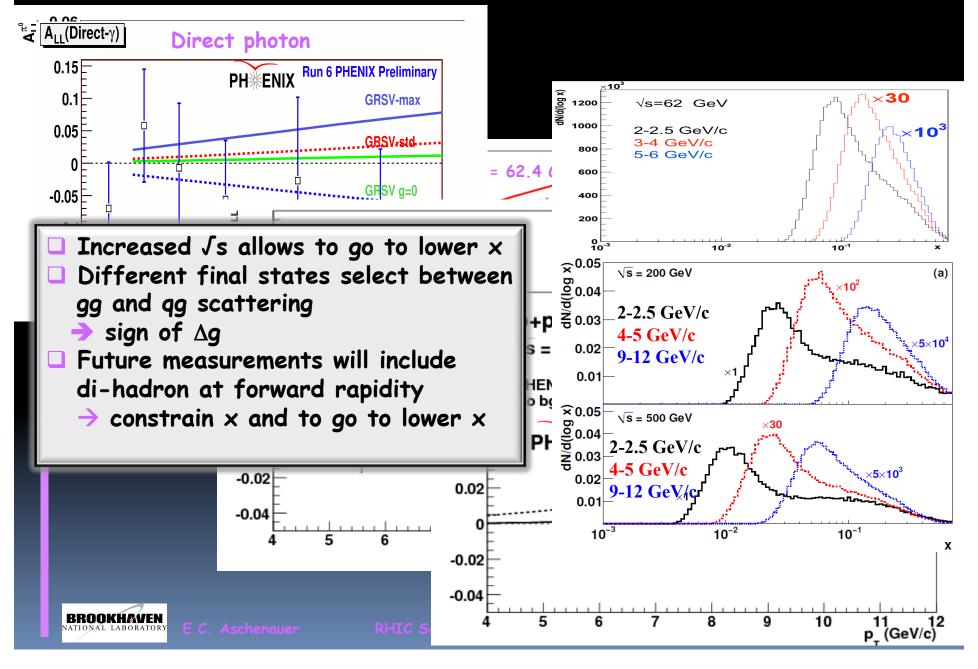
 $\rightarrow$  no longer probing  $\Delta q/q$  as in pp; but irrelevant "complication" in a global analysis



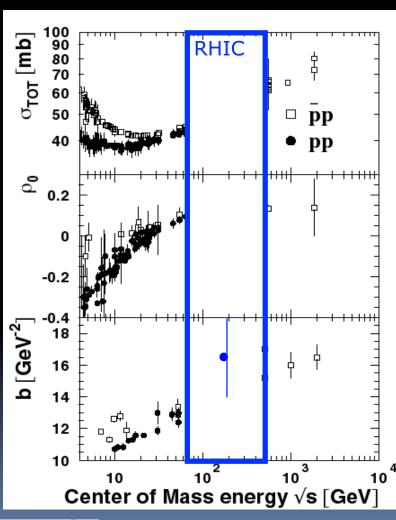
O(few hundred pb-1) each; but some "synergy effects" of combined set in global fit



### Much more data on tape and to come

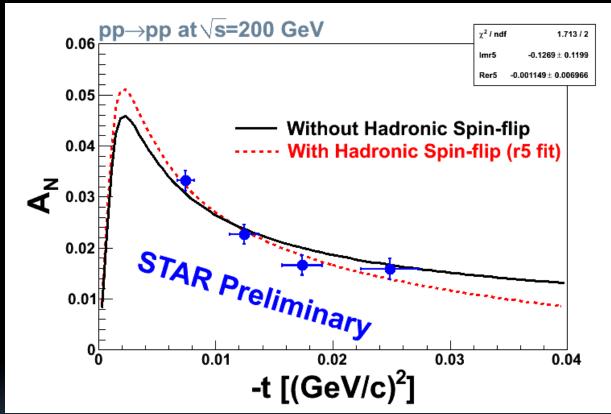


# Summary of the Existing Elastic Data



- □ Highest energy so far:
- □ pp: 62 GeV (ISR)
- □ p<del>p</del>: 1.8 TeV (Tevatron)
- □ RHIC energy range:
- Elastic measurements: Details on the nature of elastic scattering at high energy (Pomeron) are NOT well understood: Unique measurements in wide t-range with polarized beams

# First high-statistics measurement of CNI at high-energy ( $\sqrt{s}=200~GeV$ )

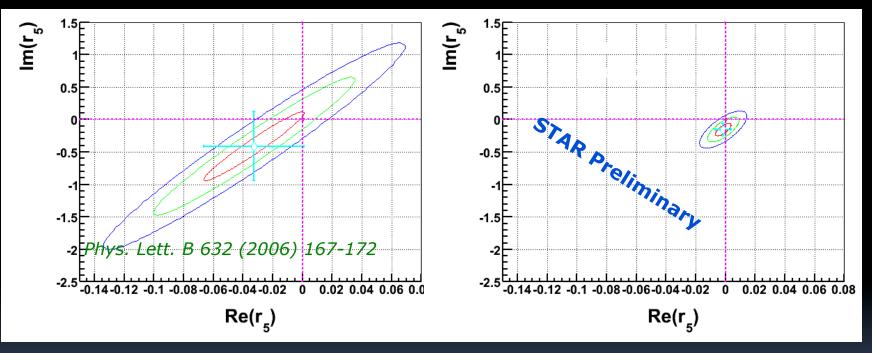


Statistical errors + systematic t-scale uncertainty (10%) in the fit
 Higher-t reach planned from the upcoming √s=500 GeV (and with Phase II set-up) at RHIC



# Hadronic Spin-Flip amplitude

pp2pp: RHIC 2003 **STAR**: RHIC 2009



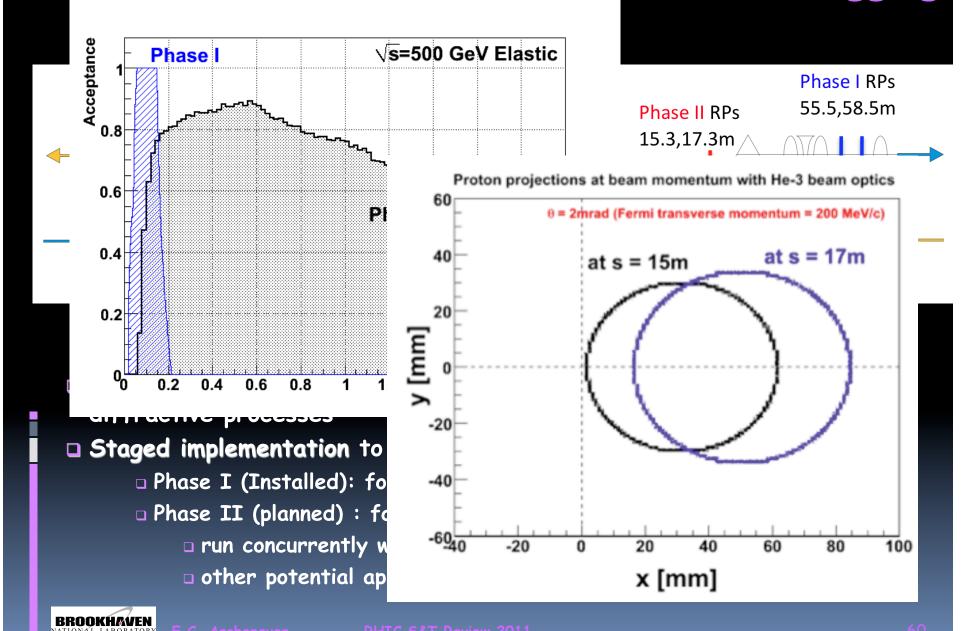
□ Fit to the data with hadronic spin-flip (r5-fit)

$$r_5 = \operatorname{Re} r_5 + i \operatorname{Im} r_5 = \frac{m\phi_5}{\sqrt{-t} \operatorname{Im} \phi_+}$$
 relative amplitude between hadronic spin-flip ( $\Phi_5$ ) and non-flip ( $\Phi_+$ ) helicity amplitudes

No significant Hadronic spin-flip required in the fit

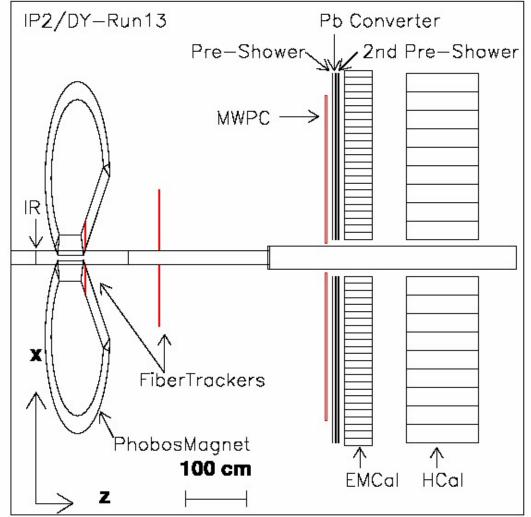


### Forward Proton Tagging



### DY Feasibility Test

- □ Staged
- ☐ Assumpti
  - **•** 1) ~4
  - 2) 12run 1
  - ◆ 3) 12 run 1
- □ Planned \$
  - Hcal estabHcal
  - Hcal of ze dilept
  - Hcal13 wiobserwheth
  - Lessons decadal plan upgrades for DY



in RHIC run 11 500 GeV in RHIC

500 GeV in RHIC

l with goals of e calibration of backgrounds

run 12 with goals =50% to observe

pole for RHIC run am=50% to um to address

heniX next

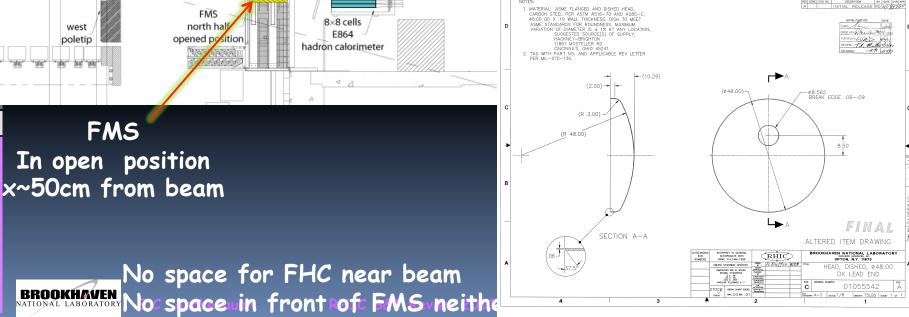
### STAR forward detectors

#### FTPC (to be removed next year)

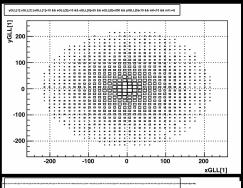
Proposed FHC (for jet & lambda)

≈ 6 L<sub>int</sub> spaghetti calorimeter 10cm × 10cm × 120 cm "cells"

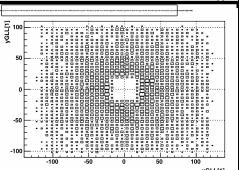
DX shell R ~ 60cm



# DY Signal

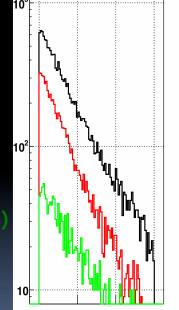


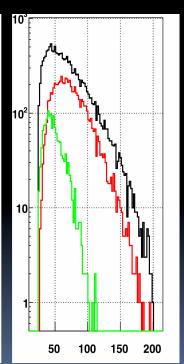
Everything η>2 14799 events pythia6.222, p+p @  $\sqrt{s}$ =500 DY process, 4M events/6.7E<sup>-05</sup>mb ~ 60/pb e+/e- energy>10GeV &  $\eta$ >2  $\times_F$ >0.1 (25GeV) 4GeV < invariant mass < 10GeV

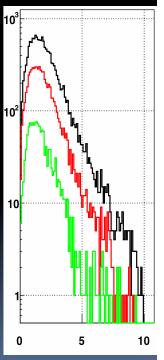


FMS closed (FHC cannot be placed due to DX magnet)

6512 events







MS open (x=5ocm) FHC (x=6ocm)

1436 events (1/5 from closed)

Inv Mass

E

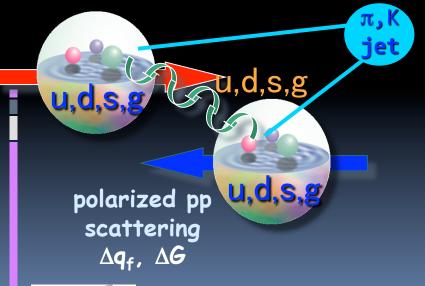
PT

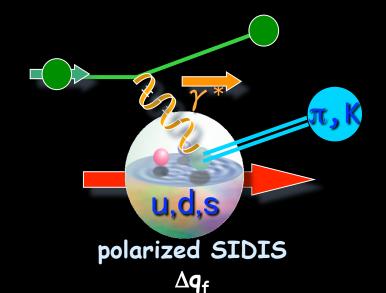
# $\Delta q$ & $\Delta G$ contributions to the proton spin

#### Existing data from:



polarized DIS $\Sigma_q \Delta oldsymbol{q}$  ,  $\Delta oldsymbol{G}$ 



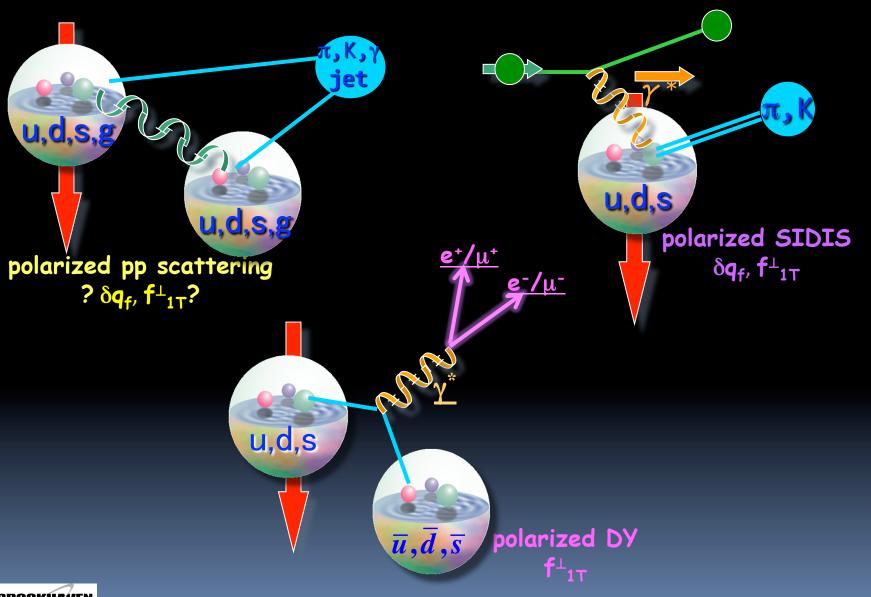


to extract polarized PDFs
! a "global QCD analysis" is required !

- □ all processes tied together: universality of pdfs & Q² - evolution
- each reaction provides insights into different aspects and kinematics
- ☐ in NLO
  - **→ D55V** PRL101:072001,2008



# Processes to study Single Spin Asymmetries



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# Star: Forward Physics program

□ add electromagnetic calorimetry at forward rapidity

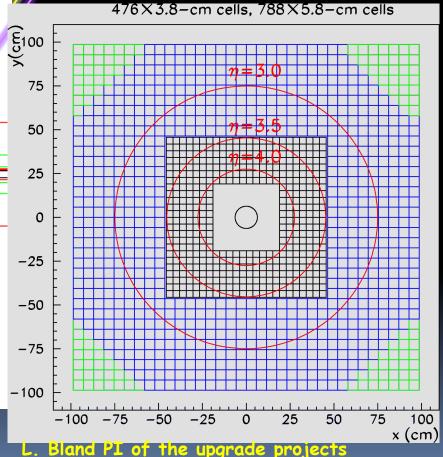
Indcap EMC

ration

 $x \sim \frac{2p_T}{\sqrt{s}}e^{-y}$ 

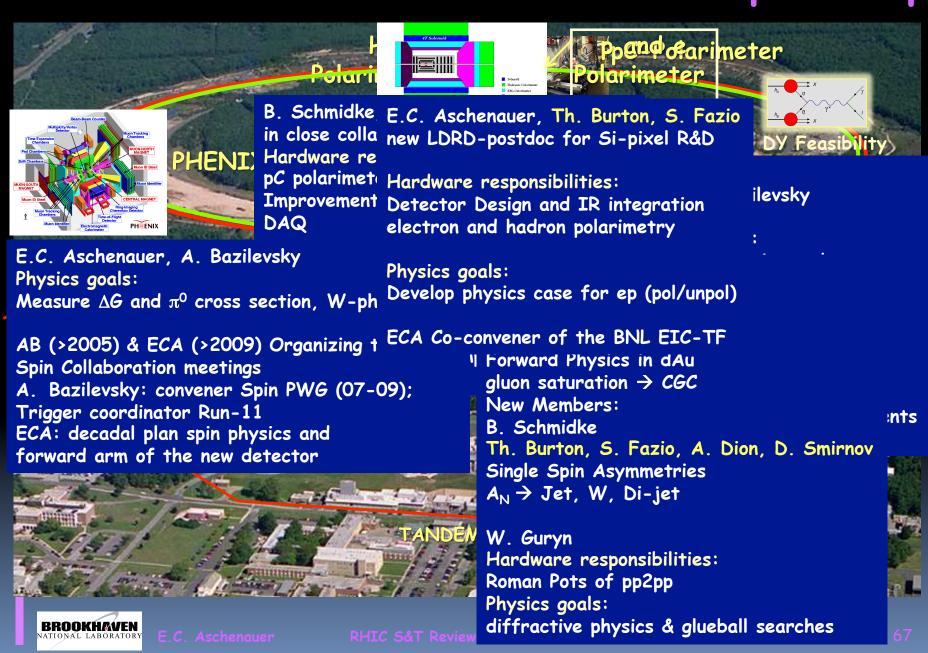
TPC: -1.0 < \eta < 1.0
BEC: -1.0 < \eta < 1.0
Solenoid Magnet

2003: FPD: 3.3 < η < 4.1 2008: FMS: 2.5 < η < 4.1

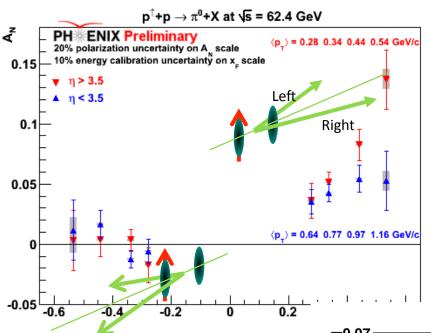


A. Ogawa and A. Gordon very important

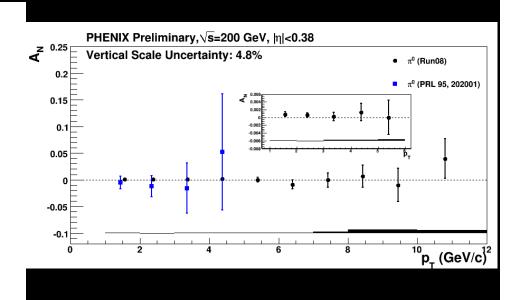
# The RHIC Spin Group

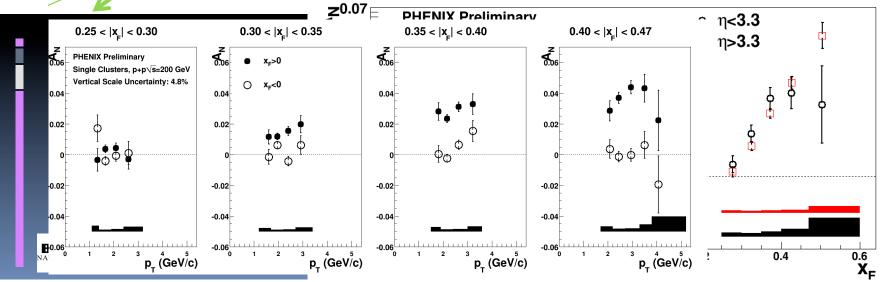


### Transverse Polarization Effects @ RHIC



**PH**<sup>\*</sup>ENIX

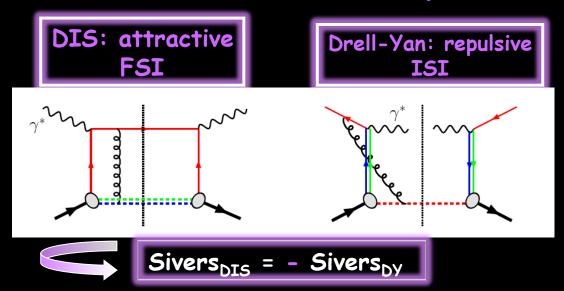




#### STAR Transverse Polarization Effects @ RHIC $p+p \rightarrow \pi^0 + X \sqrt{s} = 200 \text{ GeV}$ $p+p \rightarrow \pi^0 + X$ at $\sqrt{s} = 200$ GeV Left PRL 97, 152302 PRL 97, 152302 $\pi^{\circ}$ mesons 0.15 -Right Spin 1 3.7<η<4.15 </p> Spin ↓ $3.4 < \eta < 4.0$ Right Left .\_. Sivers (HERMES fit) $3.05 < \eta < 3.45$ twist-30.1 0.25 0 0.25 $\gamma\gamma$ mass (GeV/c<sup>2</sup>) $< \eta > = 4.00$ 0.05 $<\eta>=3.7$ $<\eta>=3.3$ 10 NLO pQCD calc. 0.5 X<sub>F</sub> 0.5 -0.510 $+p \rightarrow \text{jet}(\pi^{0}) + X \text{ at } \sqrt{s} = 200 \text{ GeV}$ **STAR** Phys. Rev. Lett. 101 (2008) 222001 $x_{\rm F}>+0.3$ (B) $A_{\mathbf{N}}$ $p+p \rightarrow \pi^0 + X$ at $\sqrt{s} = 200$ GeV • $x_{\rm f} < -0.3 \, (Y)$ $<x_{e}>=0.28$ $< x_{r}> = 0.32$ 0.08 ..... Sivers (E704 fit) FPD data Preliminary results symmetric in $\langle \cos \Phi_h \rangle$ 0.04 $p+p \rightarrow \pi^0 + X$ at $\sqrt{s} = 200$ GeV .: no confirmed contribution 0.15 from Collins Effect • $x_{\rm F} > 0.4$ 0.05 0.1 A<sub>N 0.05</sub> -0.05 -0.051.5 2.5 3.5 0.5 $p_{\scriptscriptstyle T}$ , GeV/c archiv:1012.0221 $\langle \cos(\gamma) \rangle$

# Test of Theory underlying TMDs





- Processes Universality vs non-universality:
  - ◆ Semi-Inclusive deep inelastic scattering ✓
  - ♦ Drell-Yan ✓
  - ◆ e+/e- annihilation ✓

 $p + p \rightarrow h1 + h2 + X$ arXiv:1102.4569

-Watch out for sign flips!

### Twist-3 vs. TMD

- □ Different functional form for SIDIS Sivers-fct.
  - $\triangleright$  node in  $k_T$
  - > node in x

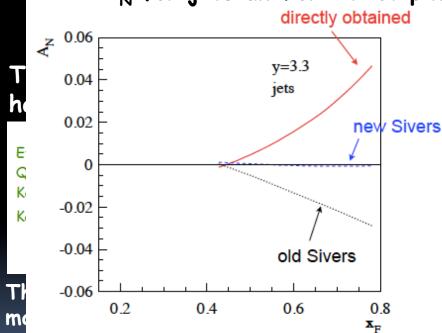


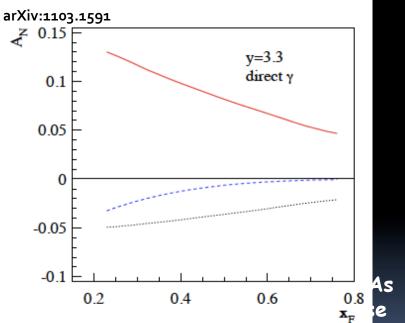
A. Prokudin, Z.-B. Kang in preparation

#### A<sub>N</sub> for jets and/or direct photon will resolve things

Current

Sidis: p, <1GeV





If the contribution trom the twist-3 tragmentation tunctions dominates, one might even reverse the sign of the ETQS function?

$$A_N = A_N | PDFs + A_N | FFs$$

BROOKHAVEN NATIONAL LABORATORY If  $A_N \mid FF > A_N$ , sign of is  $A_N \mid PDFs$  is opposite to  $A_N \mid A_N \mid PDFs$